Multi-variant experimental and numerical analysis of selected design and energetic aspects of parabolic trough collectors

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Doctoral Thesis in Environmental Engineering, Mining and Energy

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Polish title:
Wielowariantowa analiza eksperymentalno-obliczeniowa wybranych zagadnień konstrukcyjnych i energetycznych dla technologii parabolicznych koncentratorów promieniowania słonecznego

DOCTORAL THESIS SHORT SUMMARY

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Increasing the share of renewable energy generation in the total energy mix is crucial to reduce environmentally harmful gas emissions and strengthening energy security by becoming less dependent on fossil fuels, which are often the subject of international policy. In the field of useful forms of energy, low and high-temperature heat has the highest demand. One of the most efficient and environmentally friendly methods of obtaining useful heat is to absorb and convert solar energy using a collector infrastructure or solar concentrators.

Parabolic trough collectors (PTCs) are a mature technology primarily used to generate electricity by indirect heat extraction at a temperature of approximately 400 °C, most favourably in large installations located in areas with very high annual insolation. These installations were often characterised by a large aperture of parabolic mirrors, i.e. around 5 - 7 metres, an internal diameter of the absorbers of around 66 mm and a total solar loop length of up to several hundred metres. A system of solar loops connected in parallel forms a solar plant with a capacity of several hundred MW. The ongoing development of industrial installations around the world has triggered a need to develop solutions that can partially cover the heat demand in the temperature range up to around 250 °C, using the potential of renewable energy. Parabolic trough collectors with reduced dimensions, specially adapted to medium-temperature heat generation, are the most suitable solution.

Despite the maturity of the technologies utilising concentrated radiation, modifications to the geometry of absorbers and concentrators adapted to operate at lower temperature-level, have created new opportunities for intensifying heat absorption methods and reducing the cost of individual system components.

The overall aim of the dissertation was to identify the heat transfer processes occurring in a parabolic trough collector, to determine methods for intensifying heat collection and reducing the capital investment of the selected components, and to demonstrate the potential for applying these methods to specific installations. The dissertation is based on the author's four selected scientific publications, and the scope of the research itself can be classified under two main aspects that were developed in the two stages of the accomplished work.

In the first stage of the work, a test installation was comprehensively designed and constructed, whose desired functionality enabled experimental tests to be carried out for various absorbers in a parabolic solar concentrator system. To ensure stable and repeatable experimental analysis conditions, the test stand with solar radiation simulator was developed and the modelling and optimisation process is presented in paper one (*International Journal of Energy Research, publ. Wiley & Sons*). This article presents the results of optical-energy analyses that were carried out using the Monte Carlo ray tracing method. In this research, the most optimal type of light source, metal halide discharge lamps, and the geometry of the paraboloidal reflectors were determined, along with their optimal arrangement in relation to each other and to the radiation concentrator. Through optical analysis, losses due to partial radiation scattering and the potential heat flux delivered to the outer surface of the linear absorber were estimated. Based on the results obtained, the author of this dissertation comprehensively designed and constructed a test stand and carried out a series of experimental tests for different types of absorbers and methods of intensifying heat collection. The research results obtained have been presented in many conference presentations, mainly of international scope, including at conferences organised abroad. In this dissertation, the test stand and the validation of the developed mathematical models describing the heat transfer in the absorber are presented in the second article (*Energies publ. MDPI*).

In the second stage of the study, analyses were carried out to determine the application potential of methods to intensify heat absorption by thermal fluid circulating through the absorber in a parabolic trough system. Increasing installation efficiency through the sequential use of turbulent flow inserts (twisted tapes) was analysed within the scope of the second article (*Energies publ. MDPI*). Three types of inserts with a twisted ratio (*Tr*) of 1, 2 and 4 were evaluated in an installation operating in the temperature range 60 - 250 °C and with thermal fluid, mass flows of 0.15 kg/s, 0.225 kg/s and 0.3 kg/s, i.e. at parameters consistent with installations producing heat for industrial applications. As part of the study, the hydraulic and heat transfer parameters were evaluated. For the cases studied, it was determined that of the three inserts analysed, the highest energy benefit, for fluid temperatures up to 190 °C, could be obtained for *Tr* of 1. Above this temperature, an insert of *Tr* equal to 2 is more optimal. However, it should be emphasised that each of the inserts used in the case study, led to an intensification of heat absorption by the thermal fluid. In the case of the 90-metre installation analysed, the average efficiency improvement was found to be 0.27%. The analysis demonstrated that the parabolic trough collector efficiency increment, where heat intensification inserts were used, depended on their arrangement in the solar loop, the assumptions for the operation of the system and the atmospheric conditions.

Within the framework of the studies, a series of investigations into the potential application of non-selective absorber coatings were carried out, where the possibility of applying a Pyromark coating to the external surface of the absorber was demonstrated as an example. The analysis presented in the third article (*Applied Energy – publ. Elsevier*), aimed to provide a strategy for the use of extremely low-cost non-selective coatings, which are characterised by a high energy absorption ratio, but also by a high surface emissivity. The author of this dissertation has proposed a novel approach to apply these coatings only in the initial segments of the solar system, where the temperature of the heat transfer fluid, which collects heat from the internal surface of the absorber, is low enough that the higher radiation losses due to increased emissivity are overcompensated by the higher surface absorptivity in comparison to the reference cases. The analysis demonstrated that such a solution can only be applied at low concentration ratios and is strictly dependent on flow parameters and atmospheric conditions. The proposed sequential absorber arrangement enables a reduction in capital investment, as the application process for the non-selective coating is based on only one-step spray technology. The analysis showed that for an absorber with an external diameter of 33.4 mm, the price of a Pyromark coating would be $1.34/m.

The third article presents the mathematical model developed for heat transfer in a parabolic trough collector, which enabled studies to be carried out on the applicability of coatings. A new assumption applied in the mathematical model developed was to consider separately the heat delivered to the absorber surface through concentrated and non-concentrated radiation. The reason for applying this approach is because of the significantly higher proportion of unconcentrated radiation for low-aperture PTC installations than for the previously analysed wide-aperture installations. The applied detailed analytical method used in the developed mathematical model was intended to increase the analysis accuracy of the heat absorption process in low-concentration PTC installations.

The last part of the analysis deals with issues related to the tracking system, i.e. the integral part of the solar concentrator by which a mirror or mirror array continuously focuses direct sunlight onto the absorber surface. The accuracy with which the radiation is focused on the surface of the absorber is closely related to the quality of the installation, as well as the operating procedures used for the mechanism enabling the tracking movement. This aspect is also connected to the investment cost, as well as the energy consumption of tracking mechanisms.

The analyses performed enabled the assessment of the impact of the concentrator alignment deviation in comparison with perfect tracking on PTC efficiency. In the fourth article (*Renewable Energy – publ. Elsevier*), a series of numerical studies were carried out to determine the effect of tracking systems deviation on the optical and thermodynamic efficiency of low-concentration parabolic trough collectors. The analysis considered a concentrator geometry consistent with the previously mentioned radiation simulator bench. A series of analyses were also performed for the case that included no vacuum cover around the linear absorber. The results of the analyses carried out showed that the maximum deviation, which does not affect the reduction in energy input to the absorber surface, is 1.75°. It has also been demonstrated that such a deviation from the optimum position results in a more non-uniform distribution of heat flux on the absorbers surface. The curves which describe the heat flux distribution on the surface of the absorber that were obtained during the analyses can be used in future to carry out CFD analyses which will accurately demonstrate the effect of this non-uniform behaviour on the parabolic trough collector efficiency.